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Waveguide atom interferometer at LANL

Hyosub Kim, MPA-Q

Managed by Triad National Security, LLC., for the U.S. Department of Energy's NNSA.

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- Introduction
  - Cold Atom Interferometer
  - Working principle
  - Why it is matter
- Experiments
  - Motivation
  - ^{39}K BEC
  - Waveguide atom interferometer
- Discussion

Cold atom interferometer

Measurements

Acceleration

Gravity

Rotation

Fine structure constant

Casimir force

Dynamic polarizability

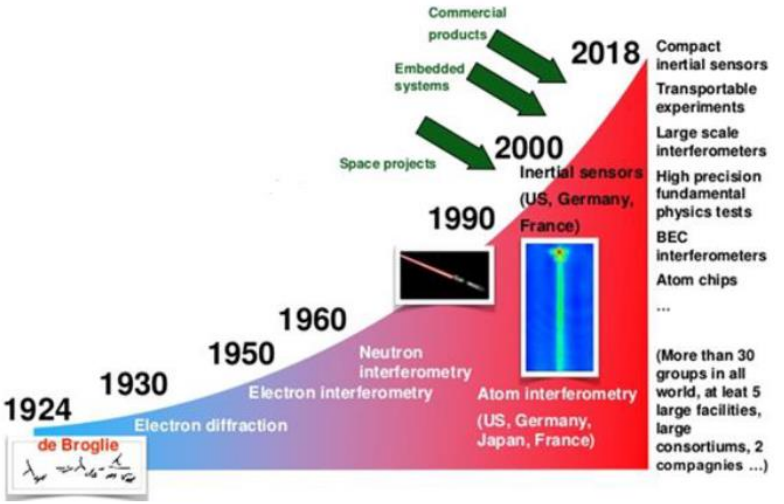
Black body radiation

Time standard

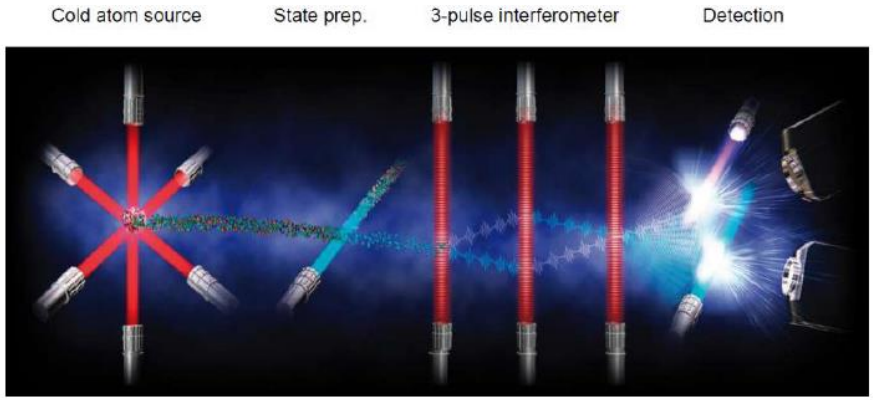
Equivalence principle

Gravitational wave

- A timeline



- Conceptual scheme



M. Travagnin, *Cold atom interferometry sensors: physics and technologies. A scientific background for EU policymaking,* 2020, doi:10.2760/315209

Working principle

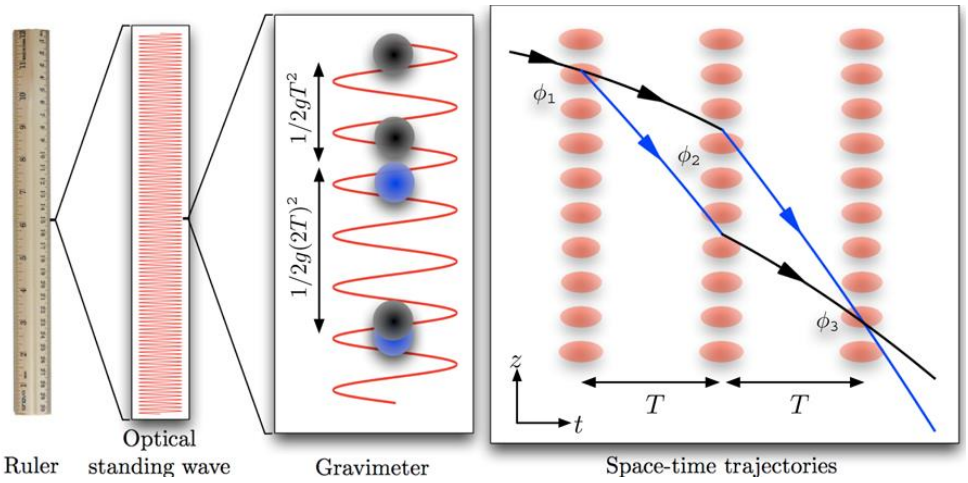
Photon momentum transfer

- Raman transition
- Bragg diffraction

Phase read-out

- Fluorescence
- Absorption image

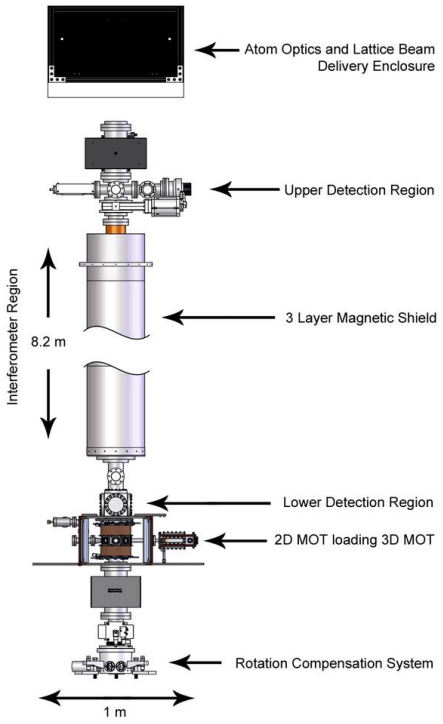
- The interferometer phase
  - The atomic motion against the ruler
  - $\phi_1 - 2\phi_2 + \phi_3$
  - Sensitive to acceleration



J. E. Debs, Ph.D. Thesis, The Australian National University (2012)

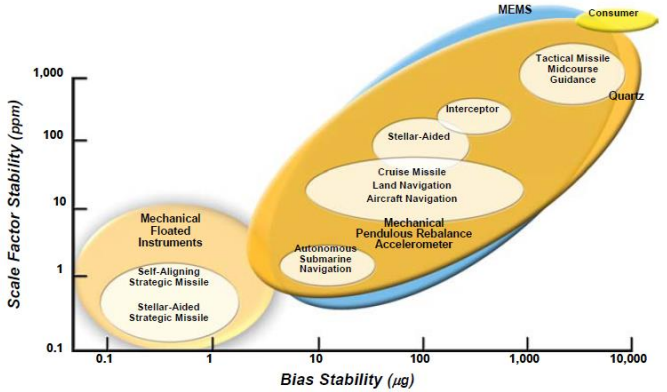
Cold atom interferometer Performance

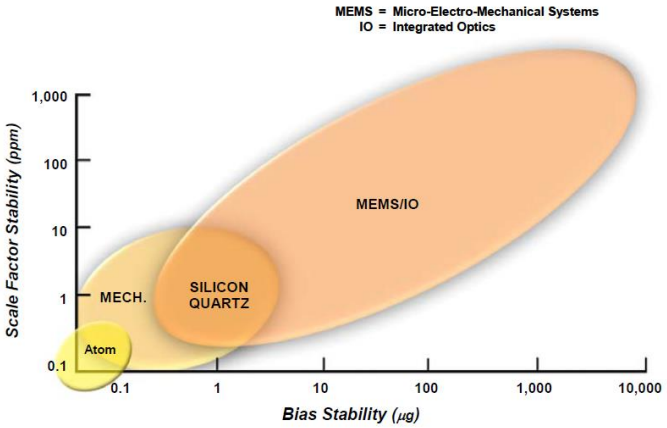
Accuracy: 6.7 pg @ 2.6 s



M. Kasevich, Stanford, 2014

- Current and future accelerometer technologies

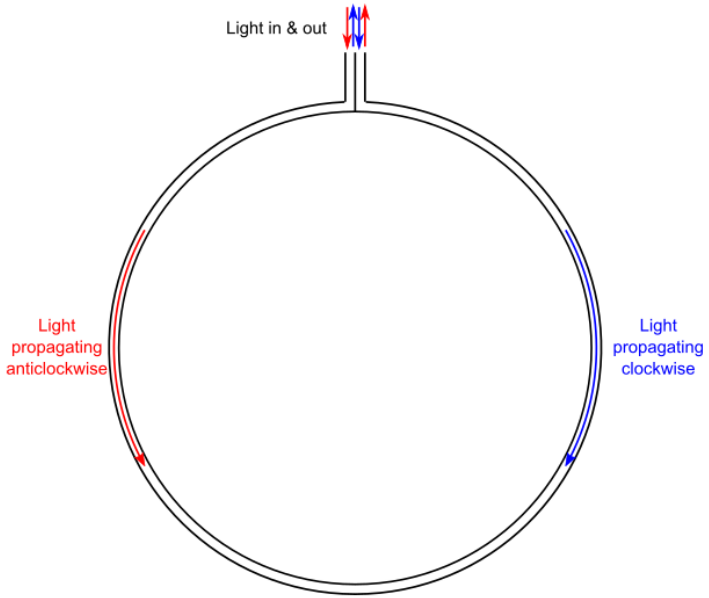


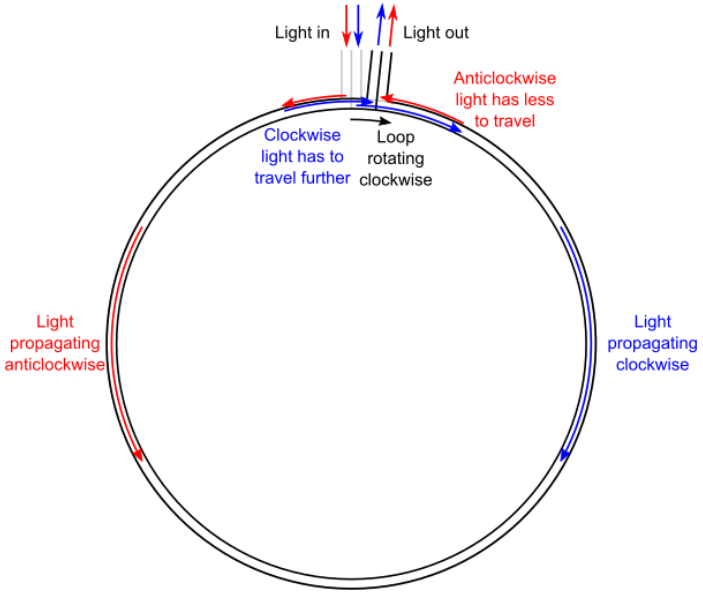


RTO-EN-SET-116(2010)

Sagnac effect

- Sagnac interferometer is sensitive to rotation





Pictures: https://www.mezzacotta.net/100proofs/archives/190

Sagnac effect

- Sagnac interferometer phase is presented [1]

$$\Phi_{\text{Sagnac}} = \frac{2E}{\hbar c^2}\boldsymbol{\Omega} \cdot \mathbf{A}$$

- Ω is the rotation, A is the area enclosed by the interferometer.
- E is the particle energy of the interfering photons or atoms
- Comparing the energy of atoms and photons

$$\frac{m_{Rb}c^2}{\hbar\omega_{633nm}} = 1.2 \times 10^{11}$$

- The scale factor of atom is huge

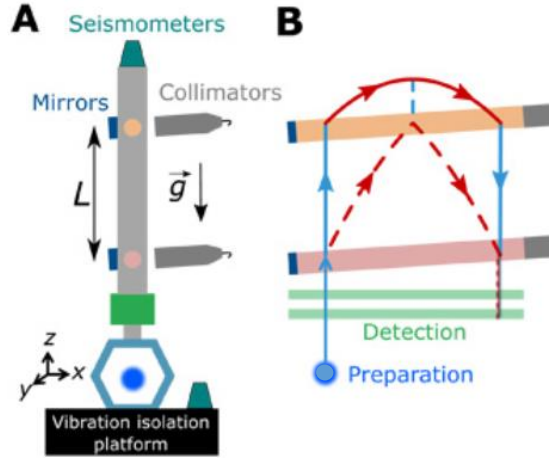
1. G. Tackmann *et al.*, Large-area Sagnac atom interferometer with robust phase read out. *Comptes Rendus Physique* **15**, 884-897 (2014).

An example of atom gyroscope

Free-space Cs fountain type: $L{\sim}60\ cm$, $T{\sim}200\ ms$

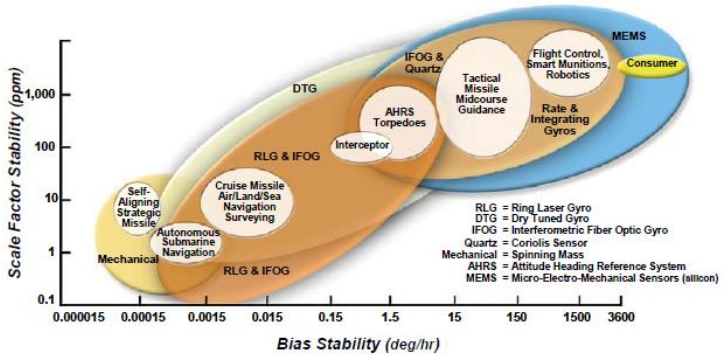
Two-photon Raman transition between clock state

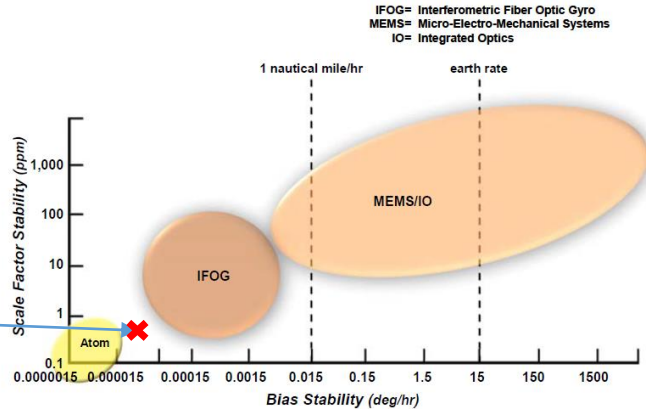
Stability $0.00006\ deg/hr$, rate $3.75\ Hz$



D. Savoie *et al.*, Interleaved atom interferometry for high-sensitivity inertial measurements. *Science Advances* **4**, eaau7948 (2018).

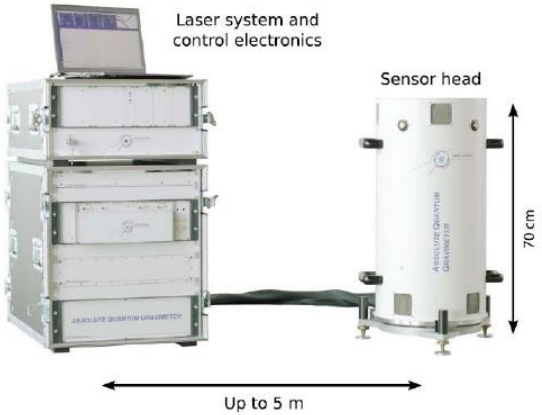
- Current and future gyro technologies

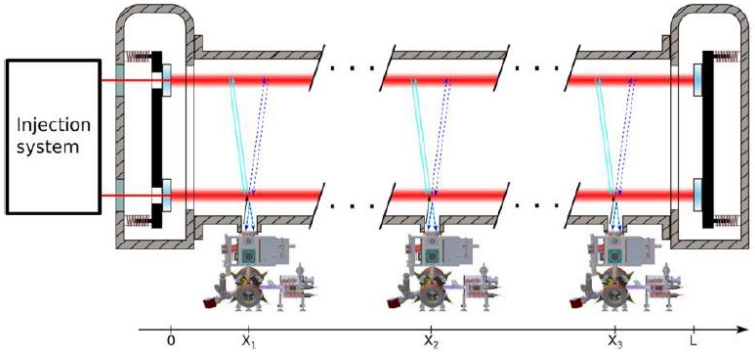


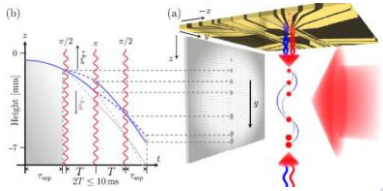


RTO-EN-SET-116(2010)

Further examples







Atom chip

Phys. Rev. Lett. 117, 203003, 2016

Portable

Scientific Reports, Vol. 8, 12300, 2018

Large scale, 200 m

Scientific Reports, Vol. 8, 14064, 2018

What could be further improvement

Typical atom interferometer

- Free space
  - Free-falling atoms
  - Expanding atom
- Cold atoms

It might be desired

- Waveguide
  - Hold atoms
- Ultracold atoms (BEC)

What we expect

Longer coherence time in a compact system size

Pros/Cons of using BEC

Advantage

- Colder and denser
  - Less dispersive
  - Longer measurement time in a compact system
  - Higher signal contrast

Disadvantage

- System complexity
  - Lower duty cycle
  - Higher cost
  - Less robust
  - Less atom number
- Denser
  - Interaction effect is pronounced

Pros/Cons of using waveguide

Advantage

- Confinement
  - Less dispersive
  - Longer measurement time in a compact system
  - Higher signal contrast

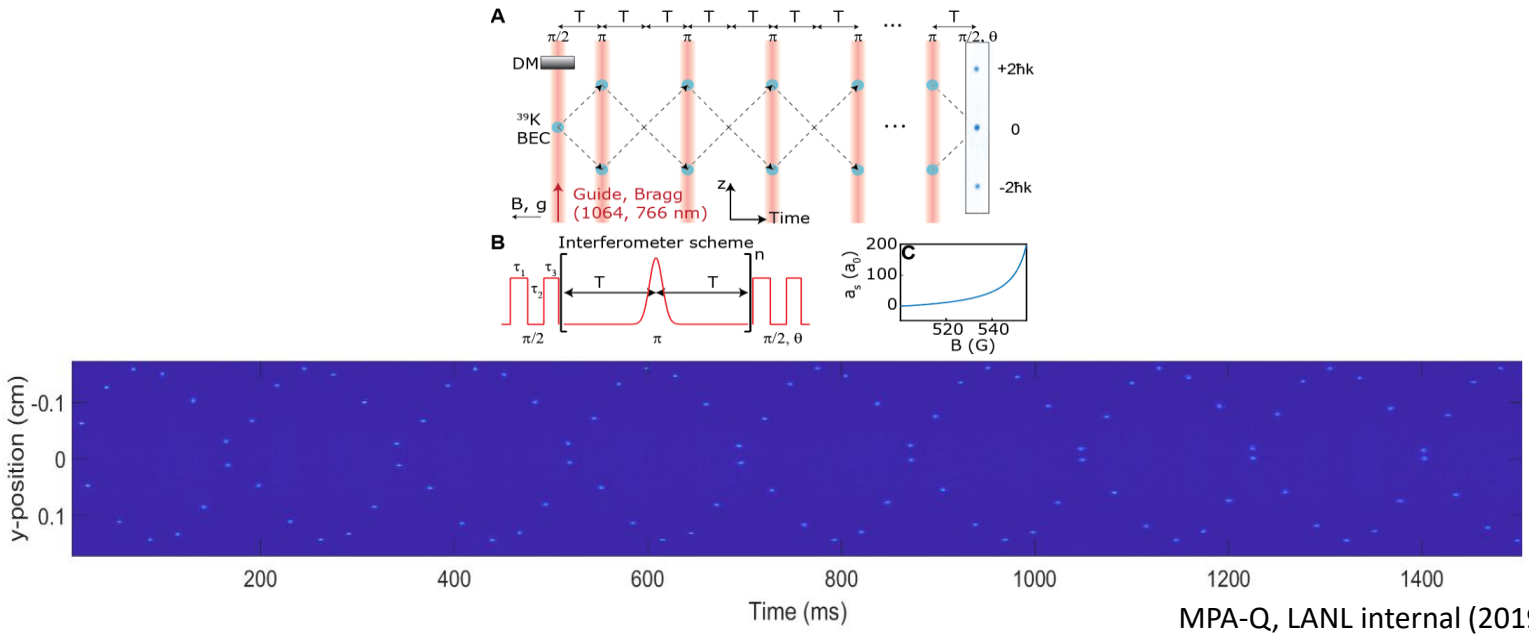
Disadvantage

- System complexity
  - Less robust
  - Waveguide fluctuation, curvature
- Confinement
  - Inhomogeneous dephasing

A waveguide BEC interferometer at LANL

- Waveguide: Loosely focused optical dipole trap
- BEC: ^{39}K |F, m_F>=|1, -1>
- Multiple-loop scheme

Overcome the disadvantages and maximize the benefits of waveguide BEC interferometer.



MPA-Q, LANL internal (2019)

Experimental goals for waveguide BEC interferometer

Overcome Disadvantages

- Dense atoms
  - Interaction effect is pronounced
- Confinement effect
  - Inhomogeneous dephasing

Tools

- Non-interacting condensate
  - Reduce wave packet dispersion
  - Reduce collisional loss and dephasing
- New pulse scheme
  - Multiple-loop atom interferometer
  - Increase available coherence time

Disadvantage1: Interacting BEC

- Gross-Pitaevskii Eq. of the condensate wave function

$$\left(-\frac{\hbar^2\nabla^2}{2m}+V_{\text{ext}}(\mathbf{r})+g\phi^2(\mathbf{r})\right)\phi(\mathbf{r})=\mu\phi(\mathbf{r}).$$

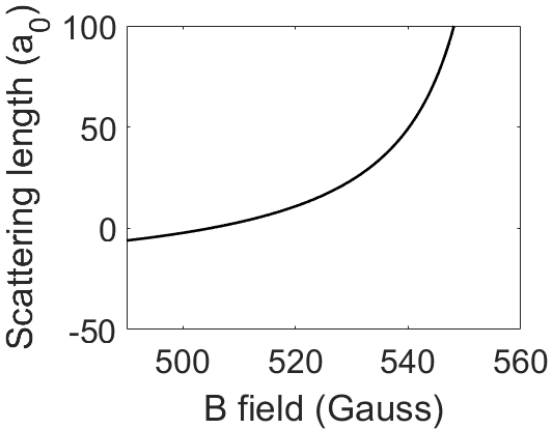
$$g=\frac{4\pi\hbar^2 a}{m}.$$

Two-body collisions characterized by the s-wave scattering length

- Solution: S-wave scattering length is tunable by magnetic field.
  - ^{39}K |1,-1>-|1,-1> s-wave scattering length [1]

$$a_s = -29a_0\left[1+\frac{56\ G}{B-562.2\ G}\right]$$

  - Evaporation at $a_s > 300a_0$ and get the condensate atoms

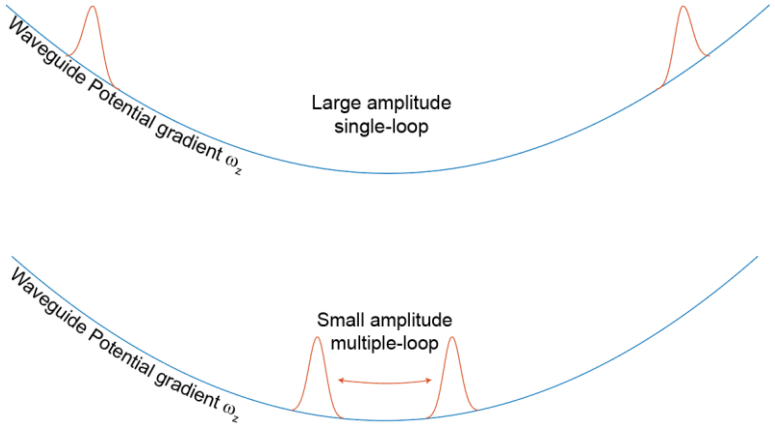


[1] C. D'Errico *et al.*, Feshbach resonances in ultracold39K. *New Journal of Physics* **9**, 223-223 (2007)

Disadvantage2: Confinement effect

Single-loop

- More inhomogeneous dephasing as atoms move farther.



Solution: Multiple-loop

- It sustains longer coherence time
- Deploy dynamic decoupling

Phase gradient of the wave packet

$$\frac{d\phi}{dz} \propto (\omega_z T)^2 \; for \; \frac{\pi}{2} \overset{T}{\leftrightarrow} \pi \overset{T}{\leftrightarrow} \frac{\pi}{2}$$

$$\propto (\omega_z T)^4 \; for \; \frac{\pi}{2} \overset{T}{\leftrightarrow} \pi \overset{2T}{\leftrightarrow} \pi \overset{T}{\leftrightarrow} \frac{\pi}{2}$$

$$\propto (\omega_z T)^4 \; for \; \frac{\pi}{2} \overset{T}{\leftrightarrow} \pi \overset{2T}{\leftrightarrow} \pi \overset{2T}{\leftrightarrow} \pi \overset{T}{\leftrightarrow} \frac{\pi}{2}$$

^{39}K BEC generation

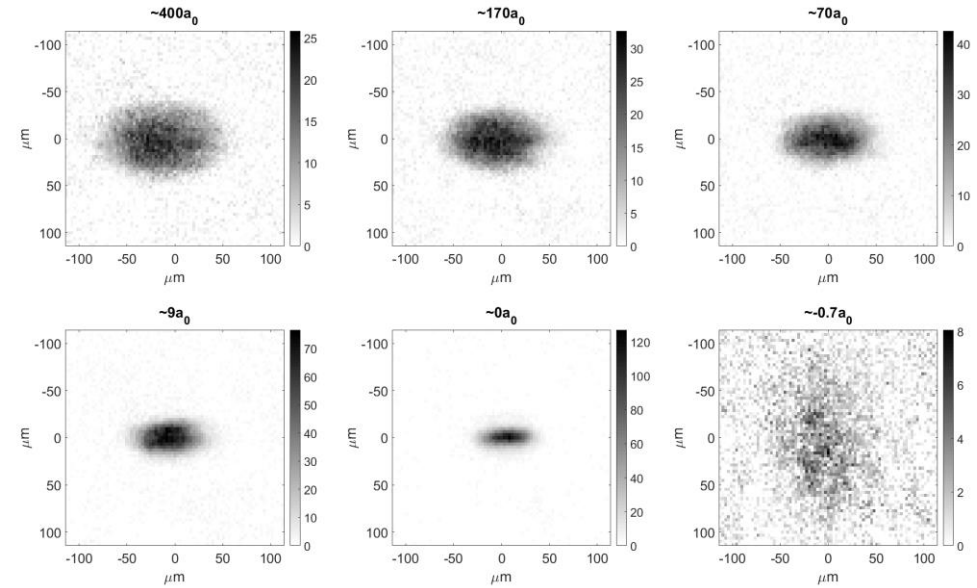
Vacuum chamber

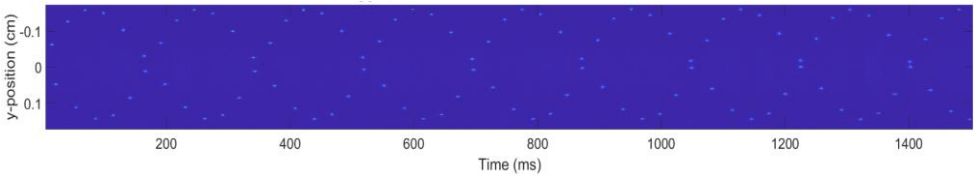
Laser cooling

Laser trapping

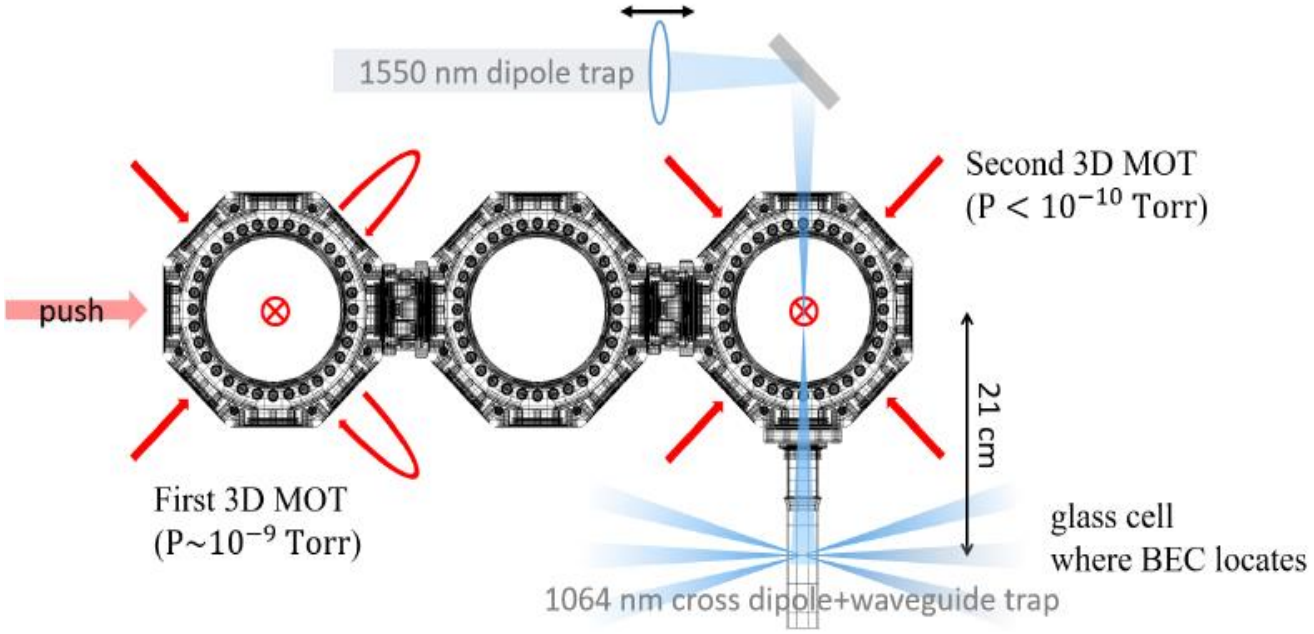
Atom transport

Forced evaporation





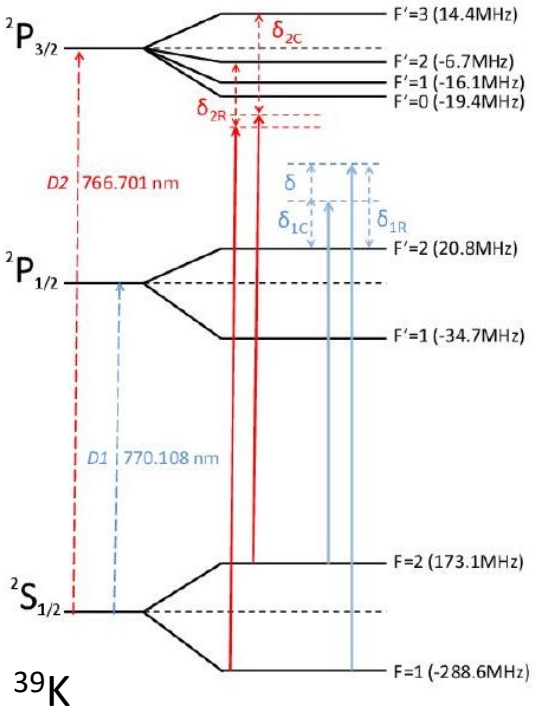
Vacuum chamber (top view)



BEC lifetime > 20 s

Laser cooling

- High pressure (HP) D2 MOT is $2{\sim}3\ mK$, pushed to the low pressure (LP) chamber.
- LP D2+D1 hybrid MOT: $\sim 60\ \mu K, 8 \times 10^{10}/cm^3$
- LP D1 gray molasses: $6\ \mu K, 8 \times 10^{10}/cm^3$



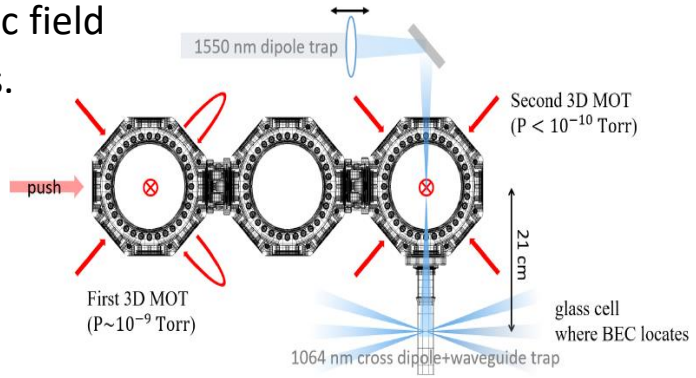
References

1. G. Salomon *et al.*, Gray-molasses cooling of 39 K to a high phase-space density. *EPL (Europhysics Letters)* **104**, 63002 (2013).
2. M. Landini *et al.*, Direct evaporative cooling of ^{39}K atoms to Bose-Einstein condensation. *Physical Review A* **86**, 033421 (2012).

1550 nm laser trapping

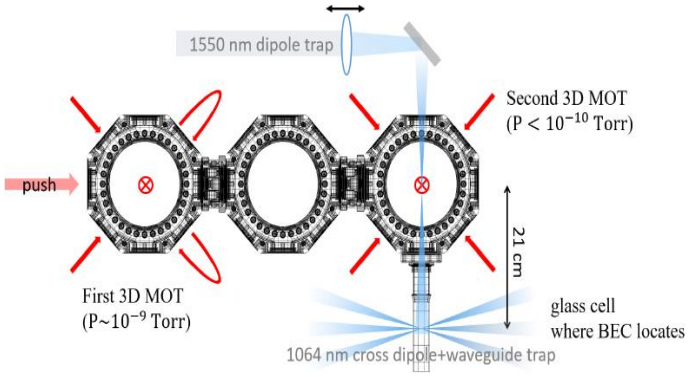
- Magnetic trap ($\sim 150\ G/cm$) holds atoms
- 1550nm Dipole trap ($w_0 = 35\ \mu m, T \sim 770\ \mu K$) is overlapped.
- The dipole trap captures the atoms
  - $\sim 10^6$ atoms, spin polarized to |1, -1>
  - $T \sim 15\ \mu K, \sim 10^{11}/cm^3$

- The atoms are transferred to the glass cell.
  - Spin polarization is maintained by Earth's magnetic field
  - Translation stage (Newport XML350) moves for 1 s.
  - No atom loss, No heating
  - Axial sloshing is observed after translation.
    - $2\pi \times \omega_z = 36\ Hz$



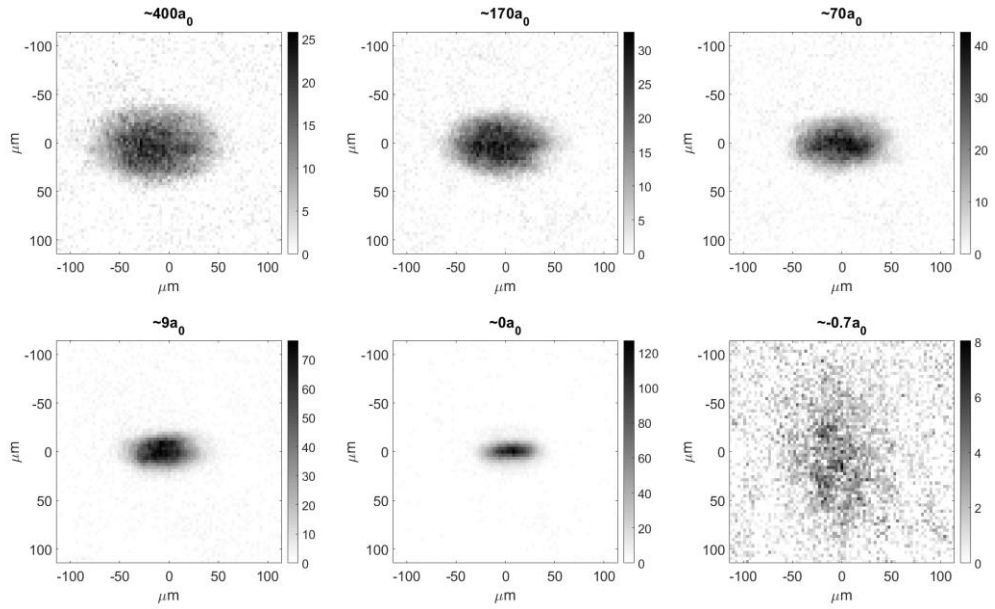
Forced evaporation cooling

- Set $a_s \sim 200 a_0$ and reduce 1550 nm beam power for 1 s.
- The atoms are transferred to 1064 nm cross dipole +waveguide.
  - Dimple effect
  - $w_0 = 100\ \mu m, T \sim 500\ \mu K$
- Set $a_s \sim 0 a_0$ and increase 1064 nm beam power for 0.2 s.
  - Adiabatic compression
- Set $a_s \sim 400 a_0$ and forced evaporation for 5 s.
  - $I(t) = \left(1 + \frac{t}{0.25\ s}\right)^{-1.45}$
- BEC is formed, $2\pi \times (77, 100, 12) Hz$
- Cross dipole power is further down to 0.
  - 1D quasi condensate, $2\pi \times (77, 100, 2.9) Hz$



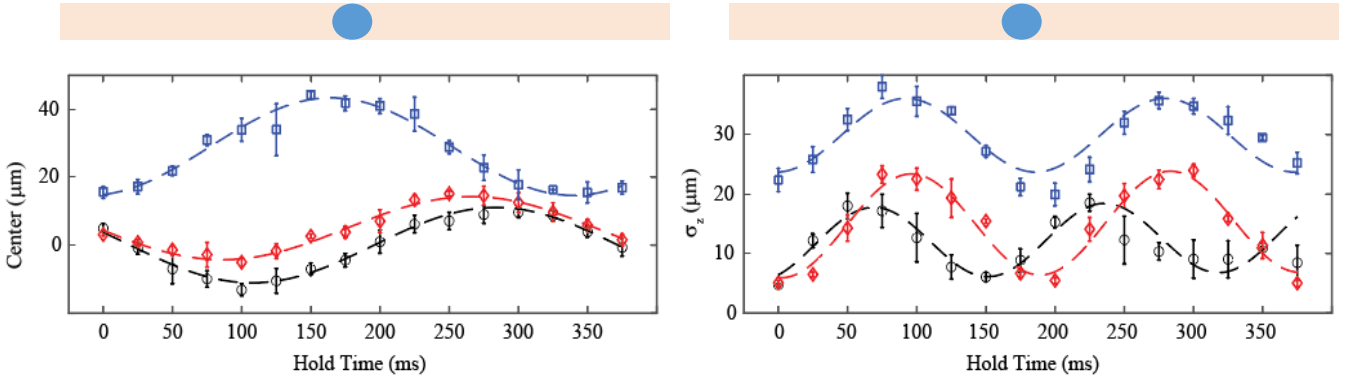
Interaction tuning of the condensate

- Absorption Images after 16 ms of time-of-flight.
  - Repulsive interaction expands the wave packet



Compressional mode

- BEC is formed, $2\pi \times (77, 100, 12) Hz$
- Cross dipole power is further down to 0.
  - 1D quasi condensate, $2\pi \times (77, 100, 2.9) Hz$

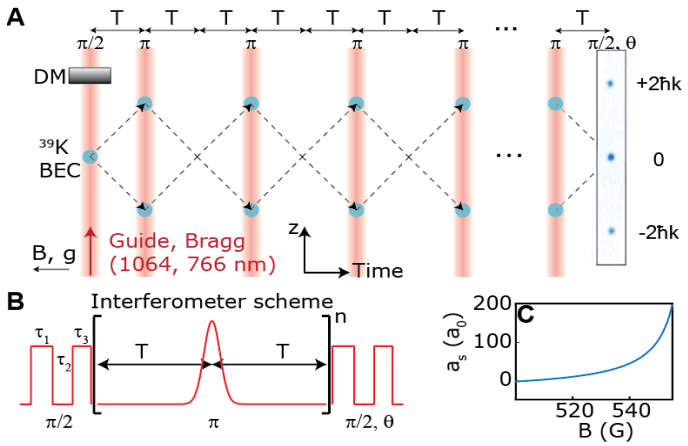


- [black, red, blue], $a_s = [-2.5, 0.7, 150] a_0$
- $\frac{\omega_c}{\omega_z} = [2.1(2), 1.8(1), 1.7(2)]$, agrees with theory [1].

[1] E. Haller *et al.*, Realization of an Excited, Strongly Correlated Quantum Gas Phase. *Science* **325**, 1224-1227 (2009).

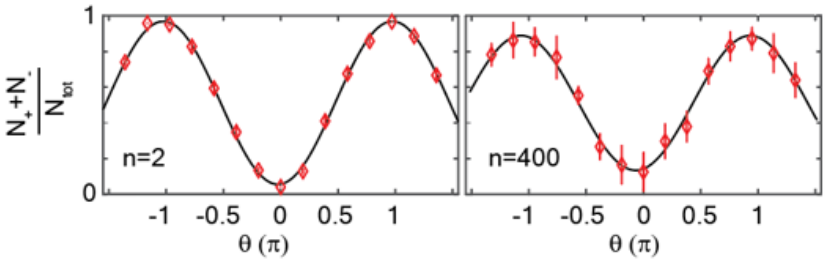
Result: Multiple-loop scheme

- Momentum is given by Bragg diffraction
- Small amplitude, many round-trip
  - Minimize inhomogeneous dephasing from confinement potential
  - Dynamic decoupling of noise: $\phi_{laser} = \phi_{\pi/2} + 2\sum_{i=1}^{n=even}(-1)^i\phi_\pi - \phi_{\pi/2,\theta}$
- Zero s-wave scattering length
  - Reduce collision induced dephasing and loss



Interferometer fringe

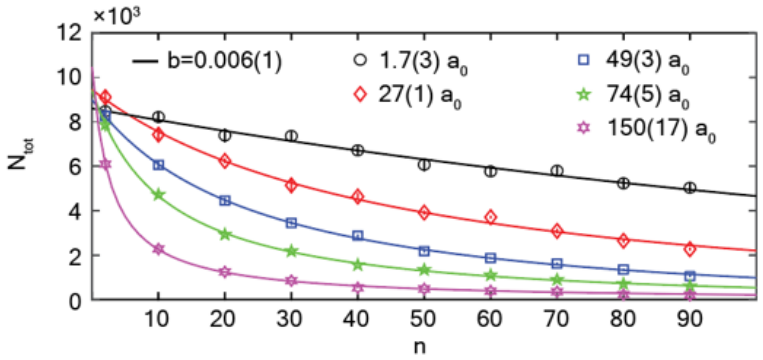
- Coherence time is 900 ms for n=400
  - T=1.125 ms
  - The s-wave scattering length: $a_s = 1.7\ a_0$

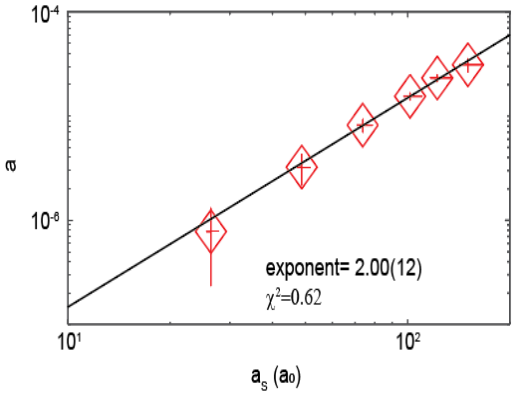


- Only atom loss limits more π pulse
  - Current π pulse efficiency: 99.4 % => $0.994^{400} = 0.09$
  - Theory: $0.999^{2000} = 0.13$
  - 4.5 s coherence time is expected

Atom loss: collisional loss + mirror pulse

- One and two-body loss model
  - $\frac{dN_{tot}}{dn} = -aN_{tot}^2 - bN_{tot}$
  - The coefficient b: π pulse loss
  - The coefficient a: colliding BEC loss
    - The scaling law holds [1]: $a \propto a_s^2$



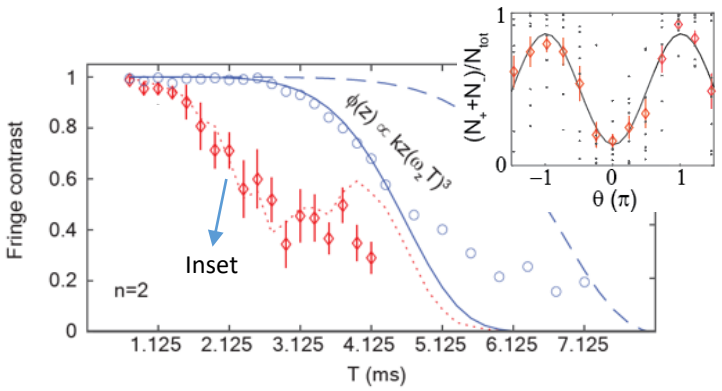


[1] Y. B. Band, M. Trippenbach, J. P. Burke, P. S. Julienne, Elastic Scattering Loss of Atoms from Colliding Bose-Einstein Condensate Wave Packets. *Physical Review Letters* **84**, 5462-5465 (2000).

Multiple-loop scheme boosts coherence time

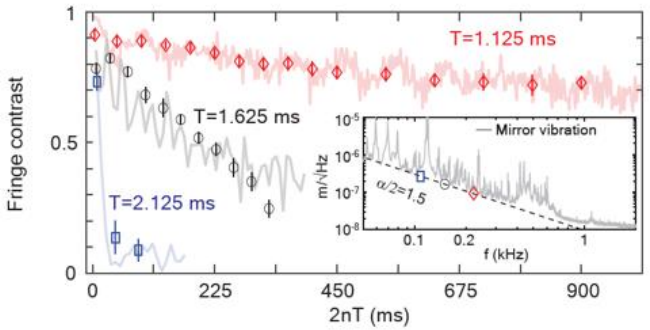
n=2 case: $\frac{\pi}{2} \overset{T}{\leftrightarrow} \pi \overset{2T}{\leftrightarrow} \pi \overset{T}{\leftrightarrow} \frac{\pi}{2}$

- Rapid degradation of fringe contrast
  - Confinement potential induced inhomogeneous dephasing (blue)
  - Mechanical noise of the reference frame (red)



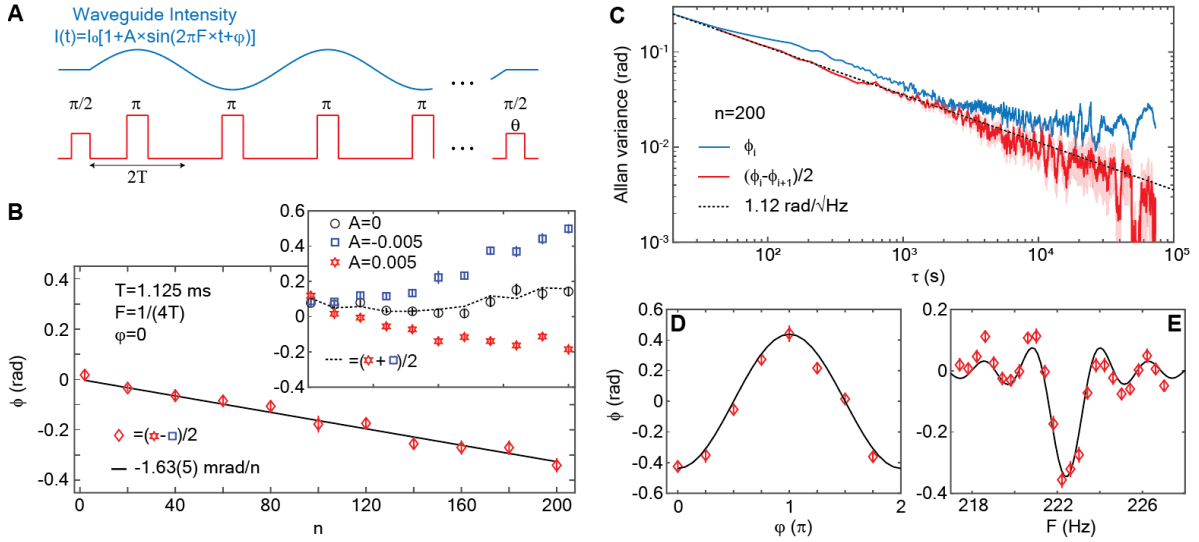
T fixed: $\frac{\pi}{2} \overset{T}{\leftrightarrow} \pi \overset{2T}{\leftrightarrow} \pi \cdots \overset{2T}{\leftrightarrow} \pi \overset{T}{\leftrightarrow} \frac{\pi}{2}$

- Sustained coherence over second
  - Minimize the dephasing
  - Dynamic decoupling of noise



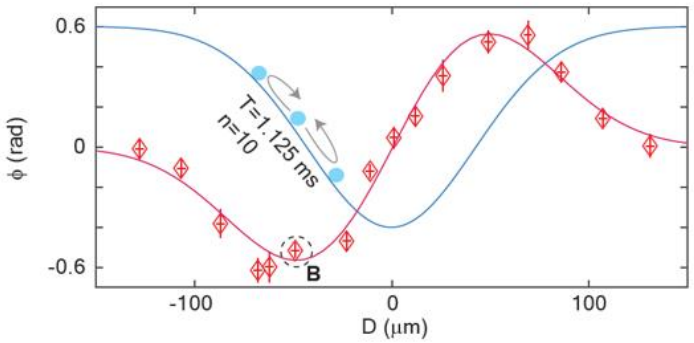
Phase sensitive AC atom interferometer: Concept proof

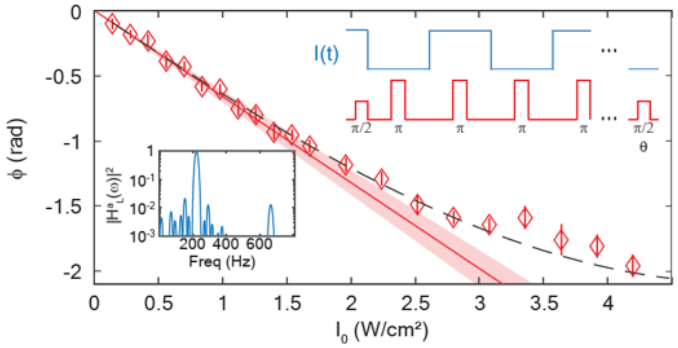
- $\phi_{laser} = \phi_{\pi/2} + 2\sum_{i=1}^{n=even}(-1)^i\phi_\pi - \phi_{\pi/2,\theta}$
  - Cancel out DC signal.
  - Accumulate a resonant frequency signal, F=1/(4T).
  - Dynamic decoupling of mechanical noise.
  - A principle of lock-in detection.



Signal measurement: AC Stark shift

- 1064 nm small beam vertically cross the waveguide.
  - Good for high gradient signal measurement.
  - The resulting dynamic polarizability from the fit: $\alpha_{1064\,nm} = 620(40)\ a.u.$
    - Shows a good agreement with the reference value: $\alpha_{1064\,nm} = 606(5)\ a.u.$ [1]

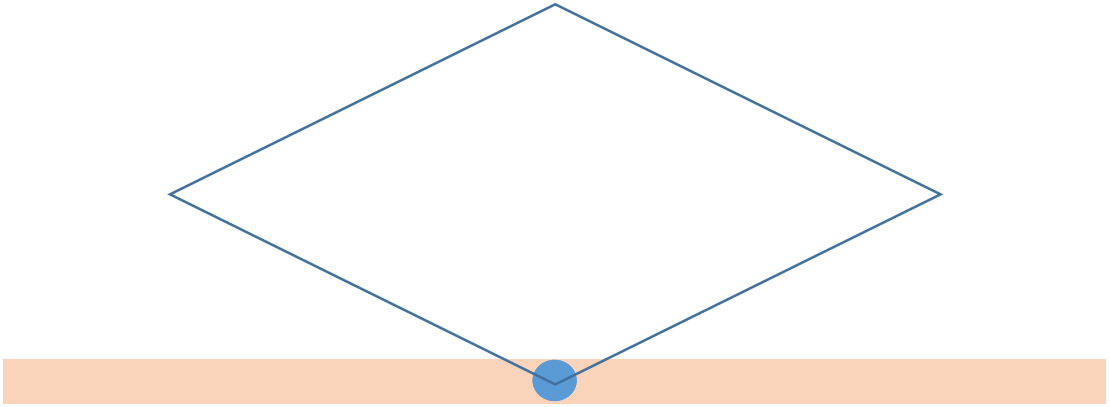




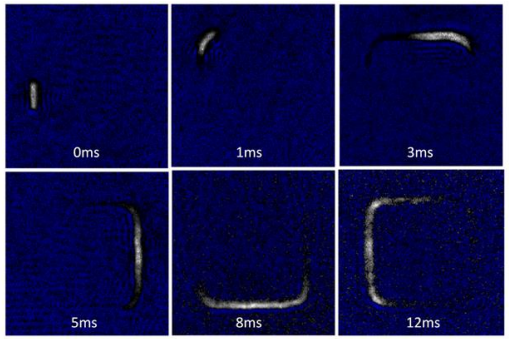
[1] M. S. Safronova, U. I. Safronova, C. W. Clark, Laser cooling and trapping of potassium at magic wavelengths. *arXiv:1301.3181*, (2013).

Future perspectives

- Moving waveguide Sagnac interferometer



- Closed-loop waveguide Sagnac interferometer



C. Ryu, M. G. Boshier, Integrated coherent matter wave circuits. *New Journal of Physics* **17**, 092002 (2015).

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